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Influence of tool texture on friction and lubrication in strip reduction

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Abstract

Tool texturing is studied as a method to enhance lubrication and prevent the occurrence of galling. Strip reduction test tools manufactured with longitudinal, shallow pocket geometries oriented perpendicular to the sliding direction are tested. The pockets have small angles to the workpiece surface and varying distance. The experiments show an optimum distance between the pockets to exist that creates table mountain topography with flat plateaus and narrow pockets in between. If the flat plateaus are too narrow, an increase in drawing load and pick-up on the tool plateaus is observed. The same occurs for too wide plateaus. A theoretical friction model supports the experimental findings of an optimum distance between the pockets, where the contribution to friction by mechanical interlocking of the strip in the pockets is limited and lubrication of the plateaus is enhanced by micro-plasto-hydrodynamic lubrication.

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Keywords: Textured tool surface; lubricant entrapment; mechanical interlocking; friction; strip reduction; ironing.

1. Introduction

The application of surface texturing to facilitate lubrication in engineering applications such as in bearings and reciprocating contacts is well known. A few tests of surface engineered deep drawing tools [1] have shown very promising results, indicating that textured tool surfaces may provide mechanical lubrication systems which can substitute chemical ones, and thereby replace environmentally hazardous lubricants with environmentally benign ones. A small pocket angle towards the workpiece surface facilitates escape of the trapped lubricant in the pockets, which increases the tool life [2]. These effects can be enhanced by utilizing transverse roughness profiles and oblong pockets oriented perpendicular to the sliding direction [3]. In strip drawing tests the lowest friction is found, when the ratio between pocket area and total area is app. 20% [4] and it is shown that increasing drawing speed enhances

the effect [5]. The present authors have found similar influence of drawing speed and that increased viscosity of the lubricant has the same effect [6] in case of strip reduction tests. They explain this by lubricant escape from the pockets due to micro-plasto-hydrodynamic lubrication, which contributes to a number of factors such as drawing load, resulting workpiece surface roughness and resistance to galling. The present study focus on a theoretical model for friction in strip reduction/ironing of a soft workpiece sliding on a table mountain-like topography of the tool surface. The model elucidates the mechanism of an array of plastic waves in the soft workpiece surface when sliding on the textured tool surface.

2. Strip reduction test

Fig. 1a shows a schematic of the strip reduction test, whereas Fig. 1b shows the table-mountain-like tool surface topography. Three surface texture features are important parameters to promote micro-hydrodynamic lubrication mechanism and to avoid mechanical interlocking in the pocket valleys [6, 7], which are 1) oblong pockets oriented perpendicular to the drawing direction, 2) small pocket angle γ and 3) shallow pocket depth d . Three different texture designs were chosen with a width of flat plateaus between the lubricant pockets $x = 0.23, 0.46$ and 0.92 mm, respectively. The oblong pockets were made with a small pocket angle $\gamma \cong 3^\circ$, width $w \cong 0.3$ mm and shallow depth $d = 7 \pm 1 \mu\text{m}$ by hard machining and subsequent polishing of the tools as described in Sulaiman et al. [7]. The pocket angle was chosen according to recommendations by Popp and Engel [2], the depth was determined by the width, which was chosen small enough to ensure a sufficient number of pockets along the tool/workpiece interface. The length of the pockets $l = 16$ mm, were smaller than the workpiece width in order to ensure pressure build-up of the trapped lubricant. The workpiece material was Al99.5-H111 strips, 4 mm thick and 20 mm wide and used in the “as-received” condition. The reduction was kept constant as $r = 15\%$. The drawing speed v was 240 mm/s.

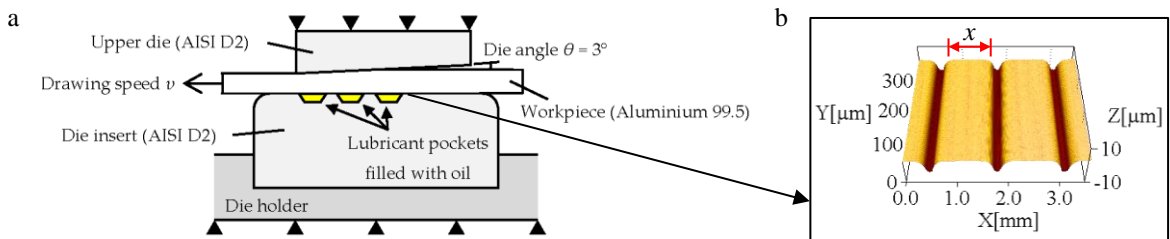


Fig. 1. a) Strip reduction testing with interchangeable die inserts and b) table mountain-like topography die surface.

3. Theoretical model of micro-hydrodynamic mechanism on textured tool surface

Fig. 2a shows the contributions to friction in the lower, textured tool/workpiece interface. They include a contribution from the metal-to-metal contact area with relative area α and a contribution from the contact between the workpiece strip and the lubricant filled pocket. Partly penetration of the workpiece material into the pocket and pressurization of the lubricant appears as shown in Fig. 2b, when loading is applied. When sliding is superimposed the workpiece material forms a wave motion moving in and out of the pocket, when passing it. At the same time the lubricant is dragged out of the pocket and thereby providing lubrication to the flat tool part by the micro-hydrodynamic mechanism as illustrated in Fig. 2c.



Fig. 2. (a) Notation, (b) compression of lubricant trapped in pocket, (c) lubrication of plateaus by lubricant escaped from the pocket.

The overall friction factor m_{tex} representing the combined friction mechanisms of the lower, textured tool surface is determined by:

$$m_{tex} = \alpha m_{met} + (1 - \alpha) m_{pock} \quad (1)$$

where $\alpha = A_{met}/A$ is the metal-to-metal contact area ratio between the flat plateau A_{met} and the total contact area A in the deformation zone. The relative area of contact between the pocket and the strip is then $(1 - \alpha)$. m_{met} is the local friction factor between the strip and the flat plateau. The local pocket friction factor m_{pock} is given by:

$$m_{pock} = m_{lub} + m_{wave} \quad (2)$$

where m_{lub} is the friction factor due to viscous drag forces between the strip and the trapped lubricant in the pockets and m_{wave} is the apparent friction factor caused by the material wave movement into and out of the pockets. The viscous drag effect of the lubricant in the pocket is assumed minimal, i.e. $m_{lub} = 0$. Thus, the local friction factor m_{pock} becomes:

$$m_{pock} = m_{wave} \quad (3)$$

The value of m_{wave} can be interpreted from work by Wanheim and Abildgaard [8]. Their model for a metallic friction mechanism is based on a plastic wave formed by the workpiece surface moving into and out of a long groove with triangular cross section in the tool. Fig. 3 illustrates the mechanism by impression of many small undulations from a hard surface on to a larger asperity of a softer surface. Subsequent sliding results in a multitude of plastic waves.

Implementing this model to the present, textured tool as illustrated in Fig. 2 the plastic wave moves into and out of the pockets experiencing an apparent friction stress $\tau = m_{pock}k$, which is plotted as a function of the tool asperity slope γ in Fig. 4. m^* is the local friction factor between the pocket surface and the workpiece. For $\gamma = 0^\circ$ thus $m^* = m_{pock}$. Due to the wave motion in and out of the pocket an extra contribution to the apparent friction factor m_{pock} appears, whereby it becomes larger than m^* . In the present case $\gamma = 3^\circ$ and assuming $m_{lub} = m^* = 0$ due to the entrapped lubricant, Fig. 4 shows $m_{pock} \cong 0.1$. Accordingly the overall friction factor m_{tex} of the textured tool in eq. (1) becomes;

$$m_{tex} = \alpha m_{met} + (1 - \alpha) m_{pock} = \alpha m_{met} + (1 - \alpha) \times 0.1 \quad (4)$$

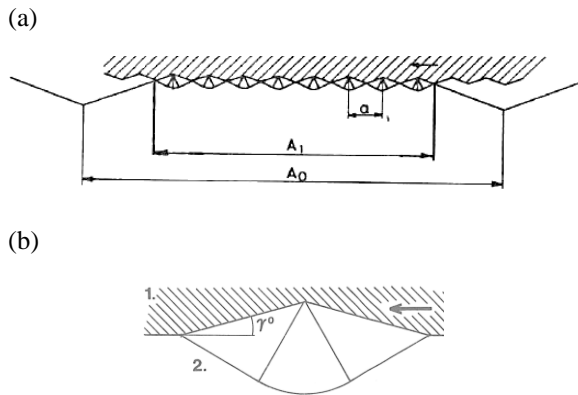


Fig. 3. (a) Array of plastic waves on top of a deforming asperity. (b) Plastic wave in a single cavity filled with workpiece material.

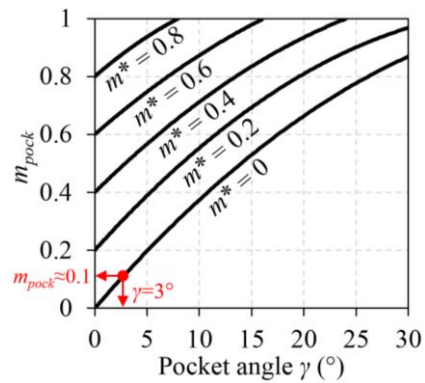


Fig. 4. Apparent friction factor m_{pock} as a result of pocket angle γ and m^* , Abildgaard and Wanheim [8].

4. Theoretical analysis of strip reduction

Based on a plane strain slab analysis, the normalized drawing stress σ_d in strip reduction through an inclined die is;

$$\frac{\sigma_d}{2\bar{k}} = \left[1 + (m_{low} + m_{up}) \frac{1}{2 \tan \theta} \right] \ln \frac{h_1}{h_2} \quad (5)$$

where \bar{k} is the mean shear flow stress in the deformation zone ($\bar{k} = \bar{\sigma}_f / \sqrt{3}$), m_{low} and m_{up} are the friction factors on the lower and upper tool surfaces respectively, θ is the die angle, h_1 is the initial sheet thickness and h_2 is the final sheet thickness.

5. Test materials

The stress–strain curve of the workpiece material Al99.5 H111 was determined by plane strain compression test. The material work hardening turned out to follow Voce's model quite well, Fig. 5:

$$\sigma_f = \sigma_o + (\sigma_\infty - \sigma_o)[1 - \exp(-n\bar{\epsilon})] \quad (6)$$

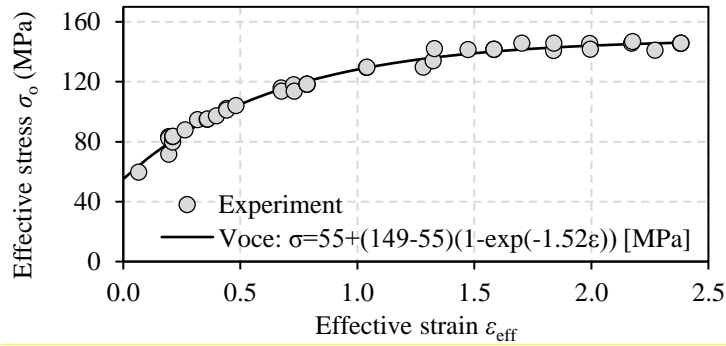


Fig. 5. Voce flow curve expression for the workpiece material Al99.5 H111 sheet.

In this model σ_o = the initial flow stress, σ_∞ = the maximum flow stress, and n = the strain hardening exponent respectively. Assuming zero prestrain and setting $\bar{\epsilon}_1$ = the effective strain of the material after drawing the following average flow stress in the deformation zone is determined:

$$\bar{\sigma}_f = \frac{1}{\bar{\epsilon}_1} \int_0^{\bar{\epsilon}_1} \sigma_f(\bar{\epsilon}) d\bar{\epsilon} = \frac{1}{\bar{\epsilon}_1} \left\{ \sigma_\infty \bar{\epsilon}_1 + \frac{\sigma_\infty - \sigma_o}{n} [\exp(-n\bar{\epsilon}_1) - 1] \right\} \quad (7)$$

The test lubricants and their properties are listed in Table 1. The Rhenus oil is a medium viscosity, mineral oil containing additives with boundary lubrication properties. The CR5 Houghton Plunger oil is a high viscosity, pure mineral oil with no additives.

Table 1. Properties of the test lubricants.

Oil type	Product name	Kinematic viscosity η (cSt @ 40°C)
Mineral oil with additives	Rhenus LA 722083	300
Pure mineral oil	CR5 Houghton Plunger	660

6. Analysis of textured tool surface

6.1. The overall friction factor m_{tex} and the drawing load

The smooth tool surface with no textures on the tool surface has a contact area ratio $\alpha = 1$. For the textured tools, the plateau distances $x = 0.23, 0.46$ and 0.92 mm results in $\alpha = 0.60, 0.74$ and 0.84 , respectively. From the experimentally measured drawing force, it is possible to determine the overall friction factor on the lower tool by applying eqs. (4) and (5) in the following way. The friction factors m_{low} and m_{up} are considered equal for the smooth, non-textured tool. The obtained friction factor $m_{low} = m_{up} = m$ is then applied to the untextured upper tool (m_{up}) for the experiments with the textured tool surfaces. This leaves only the value of $m_{low} = m_{tex}$ as unknown, which is then determined, so that experimental and theoretical drawing loads are matching, Fig. 6. Fig. 7 shows the corresponding values of the overall friction factor m_{tex} on the textured tool surface. It is noticed that minimum drawing force and m_{tex} appears when $\alpha \cong 0.8$ in good accordance with experimental findings in literature for plane strip drawing test [4].

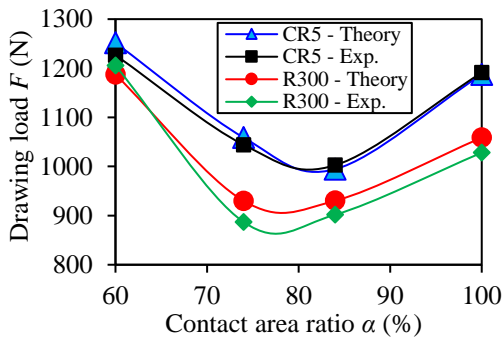


Fig. 6. Theoretical and experimental drawing load as a function of contact area ratio.

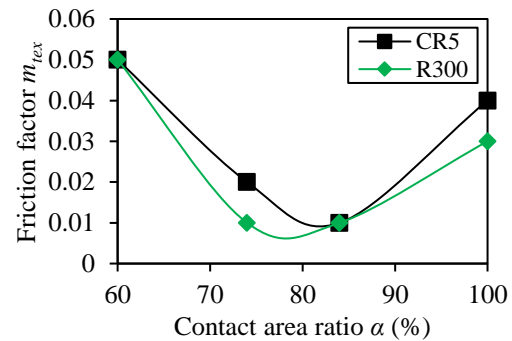


Fig. 7. Friction factor m_{tex} as a function of contact area ratio for two different lubricants.

6.2. Comparison with Wanheim-Abildgaards theoretical model

Assuming micro-hydrodynamic lubrication to occur on the flat plateaus of the textured tool surface due to the escape of the trapped oil from one pocket to its neighbour, the value of m_{met} is assumed zero. In this case, the eq. (4) is reduced to:

$$m_{tex} = (1 - \alpha)m_{pock} \quad (8)$$

where m_{pock} can be determined by Abildgaard and Wanheims theoretical model in Fig. 4. A comparison between the overall friction factor m_{tex} of the textured tools determined in this way with the one determined in section 6.1 by force measurement and slab method analysis is shown in Fig. 8. It is noticed that rather good agreement appears between the two methods.

Tool texture with too large amount of pocket area, i.e. with low α -value, was found to increase the overall friction factor. Eq. (8) explains this effect, since α becomes smaller. Too small amount of pocket area, on the other hand, may also lead to increased m_{tex} , since the lubricant escape by micro-plasto-hydrodynamic lubrication may not be sufficient to cover the entire flat plateau. This implies an increase in m_{met} in eq. (4). These two counteracting influences on m_{tex} are the reason for an optimum value of α , which gives minimum m_{tex} .

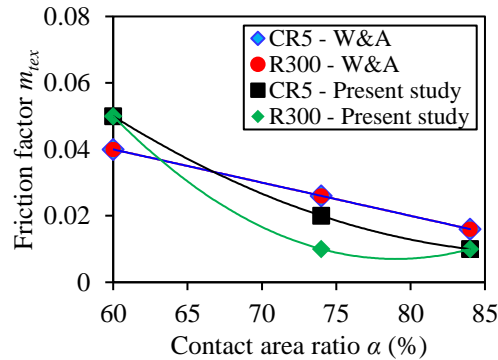


Fig. 8. Comparison of the overall friction factor m_{tx} determined by adopting Wanheim and Abildgaards model with the present calculations.

7. Conclusion

A friction model for a soft workpiece deforming against a textured tool surface was proposed. The model takes into account the plastic wave motion appearing, when the workpiece material flows into and out of local pockets between the flat plateaus of a table mountain like tool surface topography. The model was evaluated by strip reduction tests, which emulates the tribological conditions in an ironing process. The study included testing of two different lubricants, a plain mineral oil with a high viscosity, and a mineral-based oil with boundary lubrication additives having a medium viscosity. It was found out that an optimum amount of tool texture exists which reduces friction and thus draw load for the table-mountain-like tool surface topography. The overall friction factor in the interface between workpiece and textured tool surface can be satisfactorily predicted.

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